Microphysics of Magnetic Reconnection

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Abstract. Magnetic reconnection is a universal phenomenon where energy is efficiently converted from the magnetic field to charged particles as a result of global magnetic topology changes during which earlier separated plasma regions become magnetically connected. While the reconnection affects large volumes in space most of the topology changes and of the energization occur within small localized regions. Regions of special importance are the X-region and the separatrix region. The understanding of the microphysics of these regions is crucial for the overall understanding of the reconnection. The Earth magnetosphere is the only environment where the details of these regions can be studied in situ. We summarize their main properties and discuss recent spacecraft observations.

1. Magnetic reconnection

Magnetic reconnection is a universal phenomenon in astrophysical plasmas. It occurs in the Earth's magnetosphere (Phan et al., 2005; Walker et al., 1999), at the sun (Aschwanden, 2004), in accretion disks (Tajima and Shibata, 1997), etc. Reconnection is observed also in laboratory plasmas (Biskamp, 2000). Nevertheless, the most detailed *in situ* studies of reconnection have been done in the Earth's magnetosphere. In this article we give a flavour of the current level of understanding of the microphysics of reconnection, based on magnetospheric observations.

1.1. Definition

There is no commonly agreed definition of magnetic reconnection. Existing definitions are motivated by a diversity of conditions where reconnection may occur, and are not strict (Priest and Forbes, 2000). Here we use the following definition:
Magnetic reconnection is a physical phenomenon where 1) microscopic local processes cause a macroscopic change in magnetic topology so that earlier separated plasma regions become magnetically connected, 2) on macroscopic scales the system relaxes to a lower energy state converting magnetic field energy to kinetic energy of charged particles. (Fig. 1).
In practice, "macroscopic" means MHD-scales or larger, and "microscopic, local" means electron and ion inertial length-scales or gyroradii. This definition stresses three important aspects of reconnection: mi-

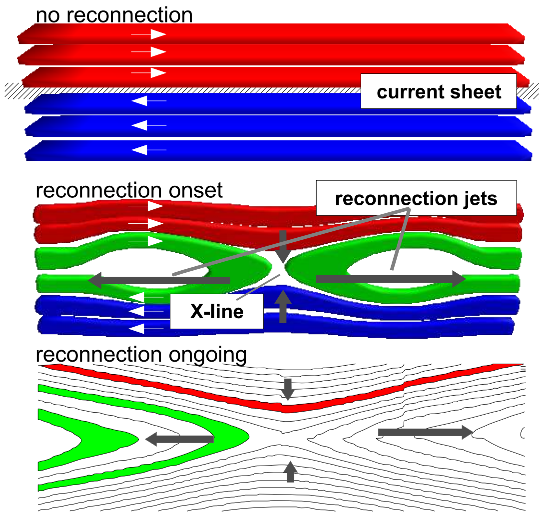

Figure 1. Schematic description of magnetic reconnection. **Top**: initially a narrow current sheet separates two different kinds of plasmas, "red" and "blue" magnetic flux tubes. **Middle**: due to a localized process "blue" and "red" flux tubes interconnect forming a new kind of "green" flux tubes; the interconnected "green" flux tubes contract due to the magnetic tension and transfer energy from magnetic field to charged particles generating reconnection jets and plasma heating; plasma from both sides can cross the current sheet along the reconnected "green" flux tubes. **Bottom**: the magnetic flux tubes as seen in numerical simulation when the reconnection process is ongoing (bottom panel, courtesy B. Rogers).

crophysics leading to macroscopic effects, topology change leading to mixing of previously separated plasmas and energy conversion.

The most studied and probably the most common type of magnetospheric reconnection occurs at X-lines and we limit the article to this case. The *X-line*, also called separator or merging line, is a line (point in a 2-dimensional, 2D, projection) along which the interconnection of magnetic flux tubes from two different plasma regions occurs (Fig. 1). In a simple cartoon, magnetic field lines are "cut" due to some microphysical processes, and then "reconnected" along an X-line in 3D space, Fig. 1.

Reconnection is ongoing when at the X-line there is an electric field E_{tan} locally tangential to the X-line (Sonnerup 1979) and reconnection has a global effect when the integral along the X-line $\int_X E_{tan}\, ds \neq 0$. The parameter E_{tan} is a measure of magnetic flux transport and defines the reconnection rate. In practice it is hard to measure E_{tan} directly at the X-line but E_{tan} should be measured as close as possible to the X-line, in the reference frame of the X-line. The case when the magnetic field magnitude is zero at the X-line is referred to as *antiparallel reconnection* or "$B = 0$ reconnection" while when there is a magnetic field component along the X-line, then this is referred to as *guide-field reconnection*. In the latter case E_{tan} is along the magnetic field, $E_{tan} \equiv E_{\|}$, and one usually speaks of "$E_{\|} \neq 0$ reconnection". The condition $\int E_{\|}\, ds \neq 0$, where $E_{\|}$ is integrated along a magnetic field line through some localized region, has been used as a general definition of magnetic reconnection (Priest and Forbes, 2000, and references therein). This definition stresses the importance of topology changes but neglects energy conversion which we believe is a major point. The *separatrix* is a surface (line in 2D projection) defined by all magnetic field lines crossing the X-line, thus representing the first "reconnected" field lines (Fig. 2). The separatrix divides magnetic flux tubes of different topology.

A number of spacecraft observations can be used to identify magnetic reconnection:
change in the magnetic topology: $E_{tan}, E_{\|} \neq 0$
change in the magnetic connectivity of plasma: magnetic field component normal to the current sheet $B_{norm} \neq 0$, distribution functions of electrons and ions transmitted across the current sheet
energy conversion from magnetic field to plasma: reconnection jets (accelerated ions) and plasma heating inside and on the sides of the current sheet (Priest and Forbes, 2000),
spatial scales: strong and localized electric fields and currents due to local microphysics processes.

In the rest of the article we concentrate on the processes that are important for the microphysics of reconnection.

1.2. Regions of interest for microphysics

Magnetic reconnection gives macroscopic consequences but depends on localized microphysics. The first models of reconnection included microphysics only close to the X-line (Sweet, 1958; Parker, 1957). However, it was soon realized that extended regions around the magnetic separatrices are also crucial (Petschek, 1964). We call the regions near separatrices where microphysics is important for *separatrix regions*. In most cases they will be the regions between the separatrix and the reconnection jet (Fig. 2).

The condition for topology change $\int E_{\|}\, ds \neq 0$ is satisfied not only in the vicinity of the X-line but also in parts of the separatrix regions. We define all the regions where topology changes as *diffusion regions*, Fig. 2. However, the change causing interconnection of previously separated plasmas occurs only close to the X-line.

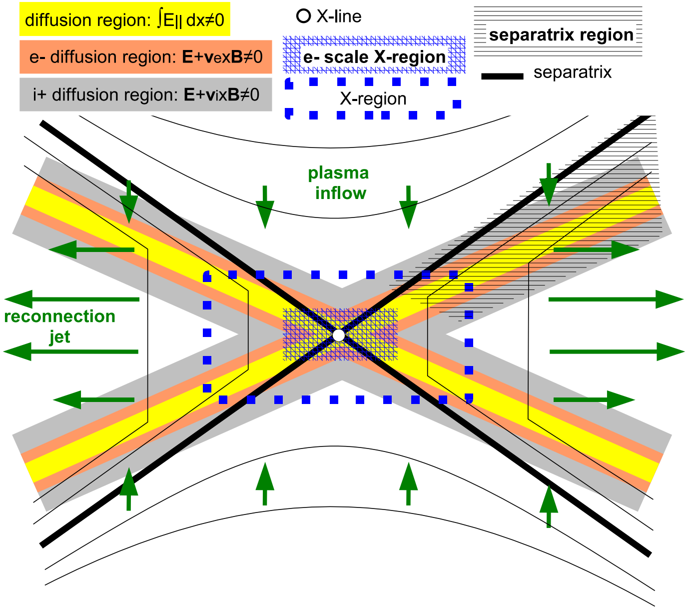

Figure 2. Sketch of all main regions of interest for microphysics of reconnection.

The terms *electron diffusion region* and *ion diffusion region* in the literature usually refer to small regions around the X-line where the frozen-in condition is broken for electrons and ions, respectively. This can result in confusion because the frozen-in condition for ions and electrons is broken also inside the separatrix regions, i.e. far from the X-line. Therefore, we use these terms to describe all regions where corresponding frozen-in conditions are not valid. Typically the smallest scales of ion and electron diffusion regions are the respective ion and electron scales, i.e., the inertial length scales or gyroradii scales. We refer to the region around the X-line on the ion scales as the *X-region* and on the electron scales as the *electron scale X-region*.

2. X-region

The probability of crossing the X-region is small because of its small size and so far there are few identified X-regions in satellite data. Most of the understanding of X-regions structure and dynamics comes from numerical simulations (Hoshino et al., 2001; Pritchett, 2001). An example of X-region observations by spacecraft (Wygant et al., 2005) is shown in Figure 3, we use it to illustrate many of the properties of this region.

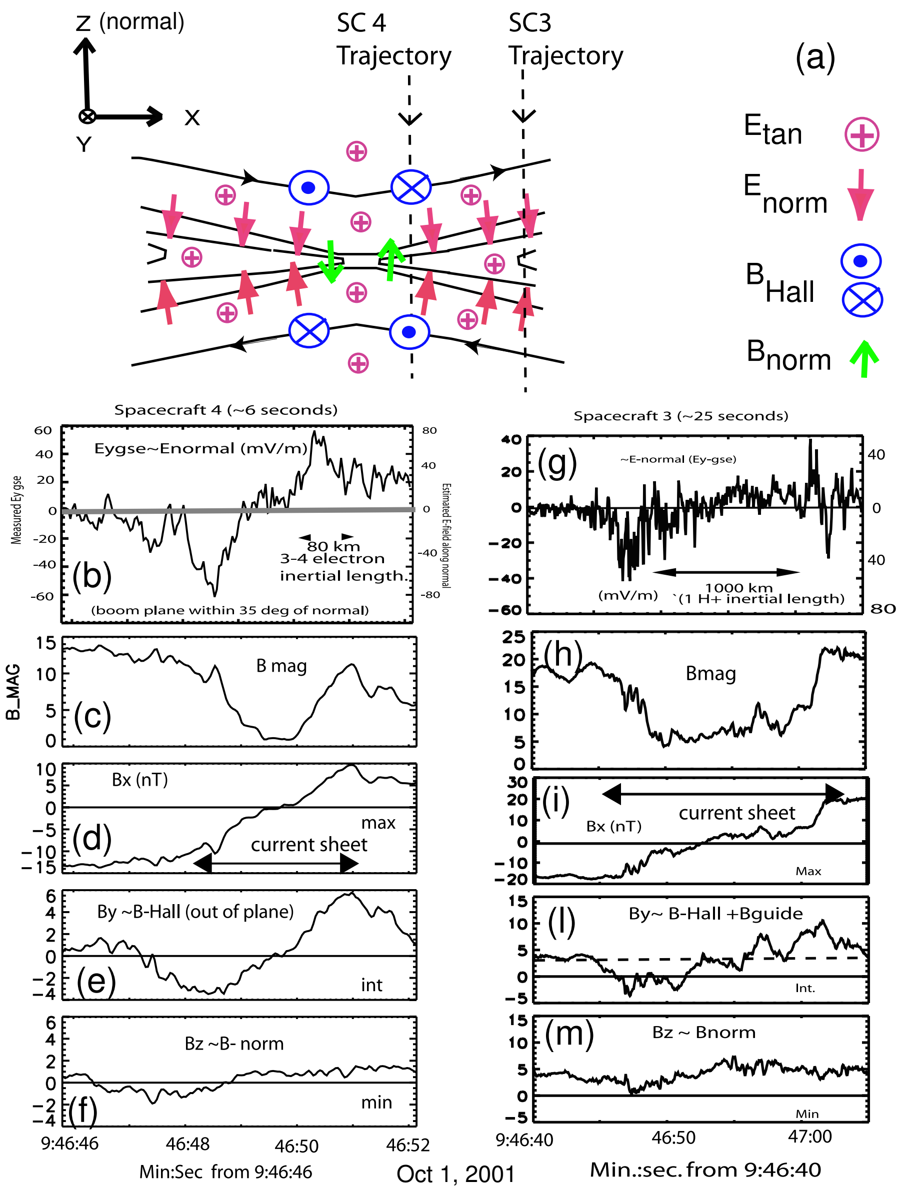

Figure 3. An example from the magnetotail showing two spacecraft crossing the X-region at different distance from the X-line. The time interval of left panels is about five times shorter than the time interval of the right panels. The same features are observed by both spacecraft but on different time and corresponding spatial scales. (Wygant et al., 2005).

There are only a few observations of E_{tan} in the X-region (Mozer et al., 2002; Vaivads et al., 2004), see a sketch in Fig. 3a. In most cases there will be at least a small guide-field magnetic field component. As described earlier, in case of guide-field reconnection $E_{tan} \equiv E_{\|}$ at the X-line. Thus, one can look for $E_{\|} \neq 0$ regions as signatures of reconnection. Such regions have been found in numerical simulations (Pritchett and Coroniti, 2004) but only a few observations exist (Mozer et al., 2003). The processes that create E_{tan}, $E_{\|}$ and support it are not yet well understood (Hesse et al., 2004).

The existence of reconnected field lines in the X-region implies a magnetic field component normal to the current sheet $B_{norm} \neq 0$. Fig.3 f,m show B_{norm} and that within the X-region B_{norm} increases with the distance from the X-line.

The thickness of the main current sheet inside the X-region gives a direct indication of the vicinity to the X-line, a current sheet of thickness λ_e is expected closest to the X-line (Wygant et al., 2005). Fig. 3d shows that the current sheet thickness observed by spacecraft closest to the X-line ($\sim 10\lambda_e$) is much smaller than that observed by the other spacecraft ($\sim 1\lambda_i$), Fig. 3i.

Inside the X-region ions are decoupled from the magnetic field. The condition $\mathbf{E} + \mathbf{v_i} \times \mathbf{B} \neq 0$ has been verified directly (Mozer et al., 2002). Due to this decoupling there is a quadrupolar out-of-plane Hall magnetic field B_{Hall} (Sonnerup, 1979; Nagai et al., 2001) and a bipolar Hall electric field E_{norm} which is perpendicular to the current sheet and much stronger than E_{tan} (Mozer et al., 2002; Vaivads et al., 2004; Borg et al., 2005). Figure 3e,l show B_{Hall} while Figure 3b,g show E_{norm} in the X-region. Simulations have suggested that the Hall physics is crucial for the reconnection process to be fast and Hall signatures in the magnetic field have been used as indicators of fast reconnection. However, the reliability of using this indicator alone has been questioned (Rogers et al., 2003). Also simulations predict different Hall fields depending on the reconnection parameters (guide-field, density, etc.), but clear cases of assymetric Hall fields have not been observed so far.

In the electron scale X-region electrons are decoupled from magnetic field. The condition $\mathbf{E} + \mathbf{v_e} \times \mathbf{B} \neq 0$ has been verified directly inside strong current filaments on electron scales (Mozer et al., 2003). Very little is known about these regions - their structure and how electrons get accelerated there are some of the questions that need to be studied.

Each of the properties discussed so far provides evidence of an X-region crossing. However, no single evidence is necessary and sufficient. Thus, only combined multiple evidence involving multiple scales and multiple spacecraft allows reliablie studies of the microphysics of X-region.

3. Separatrix region

Very few observations of microphysical processes within separatrix regions exist (André et al., 2004; Cattell et al., 2005; Matsumoto et al., 2003). Much of the understanding comes from numerical simulations (Hoshino et al., 2001; Drake et al., 2005) while the complexity of observational data can be significant (Retinò et al., 2005). Here we mention only some key properties of the separatrix regions.

As discussed before the topology changes can occur also in parts of separatrix regions, therefore it is important to study the $E_{\|}$ distribution there. This has been done by numerical simulations (Pritchett, 2001). Observations of bipolar $E_{\|}$ in solitary waves are common (Matsumoto et al., 2003; Cattell et al., 2005), however particularly interesting are those structures, such as double layers, where $\int E_{\|}\, ds \neq 0$. Preliminary observations show the existance of such structures (Mozer et al., 2005). Nevertheless the spatial and temporal distribution of $E_{\|}$ in the separatrix region is not well understood. Also, it is not clear how much of the global topology changes occurs within separatrix regions.

A significant fraction of the energy conversion should appear inside separatrix regions. A direct observation of energy conversion would require $\mathbf{E} \cdot \mathbf{j}$ estimates in the X-line reference frame. So far there are no such reliable measurements. One can also identify local energization in the particle data, for example electron beams accelerated locally inside the separatrix regions towards the X-line are found in observations (Nagai et al., 2001; Hoshino et al., 2001). Early models suggested slow shocks in separatrix regions as an energization mechanism (Petschek, 1964) but neither kinetic simulations nor observations are conclusive about this (Scholer, 2000).

Observations (André et al., 2004; Retinò et al., 2005) and simulations (Shay et al., 2001) suggest that separatrix regions extend far away from the X-region, at least up to hundred ion inertial lengths. The separatrix regions can still keep their internal structure with strong electric fields, currents and particle energization to layers on ion scales or smaller (Fig. 4). Separatrix regions extending far away from the X-region raises questions on how they may interact with boundaries such as ionosphere and how boundaries affect separatrices.

Some of the flux tubes in the separatrix regions reach the X-region. Thus, we can expect that the physical processes inside the X-region can be monitored at a distance, e.g. by monitoring parallel electron beams emanating from the X-region. Such electron beams have been observed (Nagai et al., 2001; Hoshino et al., 2001) but so far there have been no attempts to characterize the X-region by monitoring the sepatrix regions.

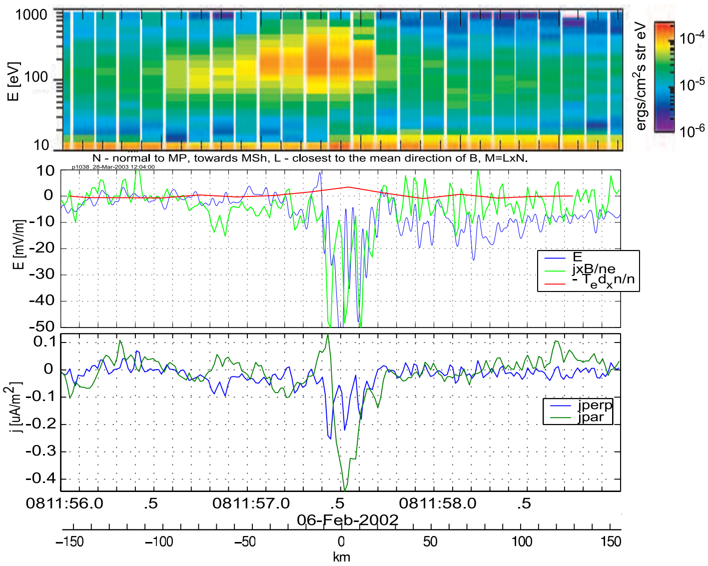

Figure 4. Example of separatrix region observations far away from the X-line. Strong currents, electric fields and electron beams are observed within an electron-scale layer. This confirms that separatrix regions can extend far away, keeping a localized inner structure where efficient microphysical processes are ongoing. (André et al., 2004).

Identification of the separatrix regions in the observations can be relatively easy if reconnection jets and clear boundaries in the electron distributions are observed (Retinò et al., 2005). Complications arise if separatrix regions are crossed either far away from the X-region or very close. In those cases additional evidence are needed, such as Hall signatures, thin current sheets, etc.

4. Summary

Many questions concerning magnetic reconnection remain. Recent simulations and available observations indicate that the X-region is essential for the magnetic topology change, but is responsible for only a small part of the energy conversion. In the separatrix regions the topology changes, but probably not in any drastic way. Rather, here much of the energy conversion occurs.

Some major remaining issues can be resolved using satellite observations. When detailed analysis indicates that observations are obtained in the X- or separatrix regions (section 1.2) an open-minded comparison with theory and simulations should be performed. In particular, inside the X-region the mechnism(s) creating and supporting the E_{tan} essential for the topology changes is of interest. In separatrix regions, direct observations of widespread energy conversion regions (observing $\mathbf{E} \cdot \mathbf{j}$, or high resolution particle distributions) would confirm our present models. Multi-spacecraft observations can distinguish between temporal and spatial variations and are of special importance for these *in situ* studies.

Acknowledgements

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